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The Absorption of Short Radio Waves in the Ionosphere

and Electric Field Strength at the Place of Reception

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THE ABSORPTION OF SHORT RADIO WAVES IN THE IONOSPHERE AND ELECTRIC FIELD STRENGTH AT THE PLACE OF RECEPTION

A. N. Kazantsev

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In the solution of most problems related to radio communication, we must necessarily come up against the question of the influence of the ionosphere on the propagation of electromagnetic waves. In an immense number of cases it is the reflection of such waves from the ionized layers of the atmosphere that is responsible for the very possibility of radio communication, as is the case for example with work in the short-wave spectrum. As A.N. Shchukin [1] has very aptly pointed out: "If it were not for the reflection and refraction of radio waves in the upper layers of the atmosphere, the role of radio as a means of communication would be diminished by ninety to ninety-five percent."

It may thus be said that the study of the ionosphere is the key to all calculations connected with the propagation of radio waves longer than a few meters.

There can be no doubt that we stand today on the threshold of a new epoch in the study of the ionosphere. Up to now we have unfortunately had to content ourselves with the results yielded by merely indirect methods of research, the most important of which is the method of the radiosonde to the upper layers, which consists [redacted] the transmission of short signals by special ionosphere stations, and their reception, after reflection back to the earth from the

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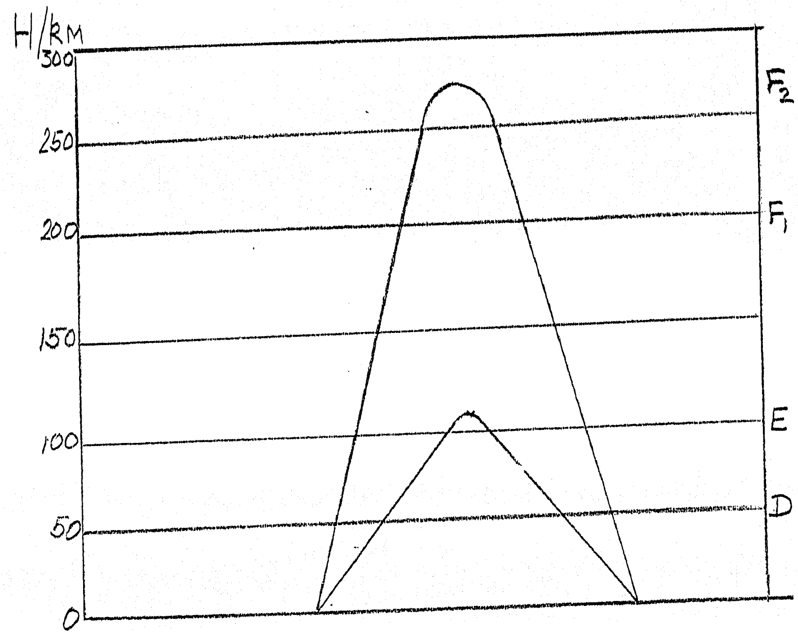
ionosphere, by the same stations.

It was proved about twenty years ago that the ionosphere has a layer structure, or in other words that several maxima of ionization are observed in it. Layers E and F are the principal layers of the ionosphere (Figure 1). Layer E, at an altitude of 100-120 kilometers, is usually responsible for the propagation of the relatively long waves. Layer F, which principally conditions the propagation of the short-wave spectrum, is stratified during the daylight hours of the summer months into layer F_1, with a reflecting altitude of the order of 200-240 kilometers, and layer F_2 at an altitude of 250-400 kilometers. At the present time it may be considered established that the so-called D layer lies below the E layer at an altitude of 60-80 kilometers, and plays a very great role in the processes of the absorption of radio waves.

The ultraviolet radiation of the sun, and, to some extent, its corpuscular radiation as well, is the principal source of the ionization of the earth's atmosphere. This ionization has a clearly expressed diurnal march which depends on the altitude of the sun above the horizon. In addition to the diurnal march of ionization, a substantial role is also played by the seasonal march, and also by the slower variation produced by the eleven-year cycle of solar activity.

During periods of maximum solar activity an appreciable increase takes place in the ionization of all layers of the ionosphere, which may be explained either by the increase of the ultraviolet solar radiation during these periods, or by the intensification of the sun's emission of corpuscular streams, some of which penetrate [redacted] the earth's atmosphere.

FIGURE 1



The stormy processes that take place on the surface of the sun not infrequently evoke ionospheric disturbances that disrupt radio communications.

Interruptions in short-wave radiocommunications, however, are not confined to the times of ionospheric storms. The causes of such interruptions are very often found in the improper choice of operating wavelengths. It is therefore a fundamental problem in the calculation and exploitation of short-wave radio communication lines to select the most advantageous wavelengths, with which the maximum receiving effect may be obtained. Very often only slight deviations (in percent) from the most advantageous wavelengths involve a sharp reduction in the electrical field strength at the place of reception; thus excessive shortening of the wave leads to its ceasing to be reflected from the ionosphere and passing beyond it without ever returning to earth. On the contrary, if the wave is too long, excessive absorption will occur in the ionized layers of the atmosphere, which again results in interruption of service.

The strength of the electrical field at the place of reception must not be less than a certain given value. It is therefore necessary to calculate the field strength created at a given distance at a definite moment of time.

To calculate electrical field strength we must know what absorption the radio waves undergo in the various ionized layers, at varying frequencies and distances, at various times of the year and hours of the day. The mechanism by which energy is absorbed in the propagation of radio waves is commonly known to be as follows: the changing field of the electromagnetic wave leads to a fluctuating motion of the charged particles in the ionized medium, by imparting an additional kinetic energy to them; in their motion the electrons or ions encounter gas molecules and collide with them; in such collisions the charged particles lose a part of their kinetic energy, which is transformed into the energy of thermal motion of the molecules. It follows from this that the electromagnetic waves must experience absorption during propagation through the ionosphere.

The coefficient of absorption γ depends on p, the number of collisions per second between an electron (or ion) and gas molecules, on the (volumetric) electron~~ic~~ ~~space~~ density N, the charge e and the mass m of the charged particle, and also on the frequency ω of the wave being propagated. The equation $\gamma = \frac{2\pi\sigma}{cn}$ (1) may be considered approximately true, where the conductivity is

$$\sigma = \frac{pNe^2}{m(p^2+\omega^2)} \tag{2}$$

and the index of refraction

$$n = \sqrt{1 - \frac{4\pi Ne^2}{m(p^2+\omega^2)}}$$

Under the conditions of radio-wave propagation in the ionosphere, the concentration of the charged particles and the number of collisions per second vary along the path of the wave. It may be considered that the properties of the medium are only slightly changed over the length of the wave when short waves are propagated in it; in that case, in investigating the propagation of radio waves, it is possible, in first approximation, to construct the trajectory of a ray according to the laws of geometrical optics.

To calculate electrical field strength at the place of reception, we must determine the value of the total absorption $\Gamma = \int_S \gamma\, ds$ along the path S traversed by the ray through the ionized region of the atmosphere.

The reflection of short waves on main lines of communication is usually from the F_2 layer. In their propagation by successive reflections from the F_2 layer and from the surface of the earth, the short waves pass through the D, E and F_1 layers, where they undergo absorption to a greater or lesser extent (Figure 1). The absorption of short waves during their passage through each of the ionized layers below F_2 must therefore be known. However, in a good number of cases, such as, for instance, on summer days at medium distances, short waves pass to the point of reception by reflection from the E layer, into which they penetrate for some distance and are partially absorbed thereby. During the daylight hours of summer, reflection of a certain band of short waves is also possible from the F_1 layer.

THE CHARACTERISTICS OF THE SEVERAL IONIZED LAYERS

Let us first of all take up the question of the parameters that characterize the several ionized layers, and of the peculiarities of the mechanism of absorption of radio waves in each of them.

1. The D layer. In the D layer, located at an altitude of 60-80 kilometers, where the density of the atmosphere is still relatively great, recombination by stages probably predominates over direct recombination. Therefore the D layer is to a considerable degree, and perhaps even primarily, an ionized layer.

In the literature there are only rough and general estimates that the ionization of layer D is of the order 10^3 electrons/cm^3. The inadequate knowledge of this value is explained, in the first place, by the fact that the ionosphere stations as a rule conduct their measurements at frequencies considerably higher than the critical frequency for the D layer, and in the second place by the basic difficulty of measuring this critical frequency, since on account of the very large number of collisions in the D layer, the signals undergo a strong fading as they approach the working frequency and the critical frequency. Based on analysis of the available materials, limits between 0.1 and 0.7 megacycles may be assumed for the critical frequency for the D layer. Raver [2] takes 0.4 megacycle as the most

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probable value of the critical frequency for the D layer. Our own analysis of the British measurements of the coefficients of signal reflection from the ionosphere during 1943-1946 confirms the view that this figure should be fairly close to the truth.

The thickness of the D layer is relatively small and may be assumed to be equal to about twenty kilometers.

We take p_0, the effective number of collisions per second at the lower boundary of the D layer, to be of the order of 10^7/sec. This figure agrees rather well with the mean value given by Raver [2], who estimates the number of collisions at the level of maximum ionization of the D layer at 3.2×10^6 per second. Starting out from this value, we obtain for the lower boundary of the layer, at a half-thickness equal to 10 kilometers, an effective number of collisions p_0 of the order of 0.85×10^7 per second.

On the basis of Penndorf's work [3] the number of collisions in the D layer is calculated to be of the order of 1.5×10^7 per second, which also is close to the value we have adopted.

It is interesting to elucidate the question of the nature of the collisions in the D layer. These collisions may be of the following character: (1) collisions between ions and neutral molecules; (2) collisions between ions and ions; (3) collisions between electrons and neutral molecules; (4) collisions between electrons and ions; (5) collisions between electrons and electrons.

Computations show that the collisions between electrons and ions, and between ions themselves, cannot reach a substantial value in the D layer, since they give corresponding figures of only the order of 10^5 and 4×10^{12} per second, respectively, which, of course, are very small in comparison to a total effective number of collisions, p_0 of the order of 10^7 per second. The collisions of electrons with electrons are likewise without influence on the order of the effective number of collisions. There remain only the collisions of electrons and ions with neutral molecules. The number of collisions of electrons with molecules, with a number of molecules of the order of 10^{16} per cubic centimeter, is about 5×10^7, or even as high as 10^8 per second, while the number of ions with molecules will probably be of the order of 5×10^5 to 10^6 per second. Thus the effective number of collisions $p_0 = 10^7$ per second lies between these figures. It may therefore be postulated that two different minds of absorption occur in the D layer: one due to collisions between electrons and molecules, and the other to collisions between ions and neutral molecules.

From this consideration of the effective numbers of collisions per second it is possible, roughly and generally, to conclude that the presence of free electrons is responsible for about one-tenth of the effective electron density N in the D layer, while the rest must be attributed to the presence of ions. It does not, however, follow that the absorption due to the collisions between free electrons with molecules, plays a small role in the D layer. On the contrary, as we shall see further on, this type of absorption, owing to the greater effective number of collisions, may be of dominating importance.

2. The E layer. On the basis of the available experimental data, on the study of the ionosphere, the half-thickness h_m of the layer may be taken as equal to about 20 kilometers.

As for the value of p_0 (the number of collisions at the lower boundary of the E layer, at altitude 90 kilometers ±), there is little data to be found in the literature. Martyn [4] gives a value $p_0 = 10^6$ per second. However, on comparing the theoretical calculations of absorption in the E layer made according to various laws of variation in ionization in relation to height, with the experimental data on the absorption of radio waves, we come to the conclusion that the figure given by Martyn is very much exaggerated.

Other investigators give the following figures for the number of collisions in the E layer:

(a) Best and Ratcliffe [5] give $p_m = 3.9 \times 10^4$ per second (where p_m is the number of collisions per second at the level of maximum ionization of the E layer), which gives, for the lower boundary of the layer, $p_0 \approx 2.9 \times 10^5$ per second.

(b) Martyn and Pulley [6] give, for the lower region of the E layer, $p_0 = 2.7 \times 10^5$ per second.

(c) Mitra and Rakshit [7] give $p_m = 2.7 \times 10^4$ per second and $p_0 = 2.7 \times 10^5$ per second.

(d) Appleton [8] presents, for altitude 120 kilometers, the value $p_{120} = 10^4$ per second, which gives for the lower boundary of the layer $p_0 = 2 \times 10^5$ per second.

Comparison of the computed data with the experimental led us to the conclusion that the effective value of p_0 in the E level should be taken at 2×10^5 per second (for summer), which agrees fairly well with the above-cited experimental figures given by a number of authors [5, 6, 7, 8].

For winter, when the E layer is somewhat higher than in summer, the assumed number of collisions should be somewhat reduced by comparison with the summer. We take $p_0 = 1.5 \times 10^5$ per second, and for the period of the equinox the mean value between summer and winter.

The question of the essential nature of the collisions in the E layer is directly connected with the effective number of collisions. In this layer the collisions of ions with neutral molecules and those between ions themselves cannot play an appreciable role, since the order of the collisions of the former kind is computed to be only 10^3 per second, and that of the latter kind 10^4 per second (with a number of ions of the order of 10^9 per cubic centimeter). The collisions between electrons themselves may likewise be neglected. There thus remain only the collisions of electrons with neutral molecules and ions.

A number of authors assume the number of ions in the E layer to be very high, of the order of 10^9 per cubic centimeter. In this case the number of collisions between electrons and ions should be of the order of 5×10^6 per second [9]. Such a number of collisions, however, would be expected to lead to a far higher absorption in the E layer than actually observed.

As for the number of collisions between electrons and neutral ions, its calculated order (a one-digit number $\times 10^5$) agrees rather well with that adopted by us on the basis of experimental data.

Thus analysis of the acceptable number of collisions leads us to the conclusion that the collisions in the E layer consist principally of those between electrons and neutral molecules, rather than with ions. Consequently we cannot admit that the space density of ions in the E layer attains the order of 10^9 per cubic centimeter.

Appleton [10] refers to the work of Massey, which showed that the process of combination of electrons with the neutral molecules, and of their dissociation from them, proceeds in such a way that there is an approximately constant ratio between the space density of negative ions and electron density -- a ratio which for the E layer is of the order of 100. Since the space density of electrons in the E layer is approximately $10^5 el/cm^3$, the number of ions per cubic centimeter should be only of the order of 10^7, which agrees well with our conclusions.

The partisans of the ionic character of the E layer point out that -- so they say -- magneto-ionic splitting ~~diffraction~~ [~~magnetoionicheskoye rasshchepleniye, presumably refers to the electromagnetic diffraction of short waves by ions~~] of a ray is but rarely observed in the E layer; this is not convincing, inasmuch as according to the data of the ionosphere station at Tomsk, such splitting ~~diffraction~~ regularly occurs, though the strong absorption of extraordinary components make it difficult to observe. The presence of these extraordinary components may, however, be noted in the group lag in the reflection of a signal from the higher layers.

We thus come to the conclusion that the absorption in the E layer is principally determined by the collisions of electrons with neutral molecules, and, to a lesser degree, with ions.

3. The F_1 layer. The number of collisions p_0 at the lower boundary of F_1 may be taken as equal to $\sim 10^4$ per second, on the basis of the data in the literature, and also of considerations resulting from our own calculations.

The F_1 layer is basically a layer of electrons, as the regularly observed splitting ~~diffraction~~ of a ray into ordinary and extraordinary components clearly indicated. Absorption in this layer is primarily determined by collisions of electrons with neutral molecules. Together with this, the collisions between electrons and ions also play a certain role. The other types of collisions (ions with molecules and ions with ions) are of no practical importance here.

Since the effective number of collisions in the D, E and F_1 layers is primarily determined by the collisions of electrons (or ions) with neutral molecules, it may be assumed that throughout the entire region of the ionosphere, from the D layer up to the F_1 layer, the number of collisions varies according to altitude by the barometric formula

$$p = p_0 e^{-\frac{h}{H}} \qquad (4)$$

where H is the altitude of the uniform atmosphere ($H \approx 10$ kilometers for the D and E layers, but ≈ 15 kilometers for the F_1 layer, in consequence of the increase in gas temperature with the altitude).

4. The F_2 layer. In consequence of the low density of the gas, the number of collisions of electrons (and a fortiori of ions) with neutral molecules in the F_2 layer (at an altitude of 250 - 400 kilometers) is very insignificant. Since the disappearance of free electrons in the F_2 layer bears the character of direct recombination, the presence of negative ions in this layer may be neglected.

The order of the calculated number of collisions of electrons with ions in the F_2 layer agrees well with the experimental data of White and Brown [11] and of others (an average value of 3.5×10^3 per second).

This character of the collisions in the F_2 layer renders inapplicable the barometric formula for determining the variation, with altitude, of the number of collisions. For this reason we assume in first approximation that the number of collisions in the F_2 layer does not depend on altitude. Since the volume density of electrons, and consequently that of ions, varies according to season and time of day, the effective number of collisions will also vary together with it. Thus we assume that p is proportional to N_{max}.

It should be borne in mind that according to the formula introduced by Ginzburg and Al'pert [9], the effective number of collisions between electrons and ions falls with increasing temperature. This circumstance plays an important role for the F_2 layer, the temperature of which apparently attains very high values (of the order of 1000 degrees Kelvin).

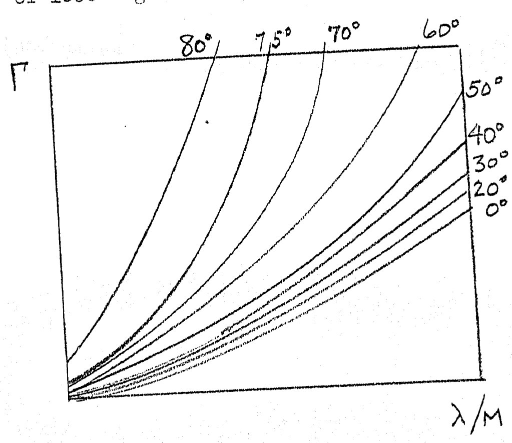

Figure 2. Absorption coefficients for the D layer.
$p_0 = 10^7$ per second; $N = 10^3$ el/cm^3.

THE ABSORPTION COEFFICIENTS FOR PASSAGE OF WAVES THROUGH THE IONIZED LAYERS AND FOR THEIR REFLECTION THEREFROM

On the basis of analysis of the mechanism of absorption in the several ionized layers and the parameters that characterize those layers, we conducted detailed calculations of the absorption of radio waves in the several layers, at varying values of maximum ionization in them, and for various laws of variation of ionization with altitude [12].

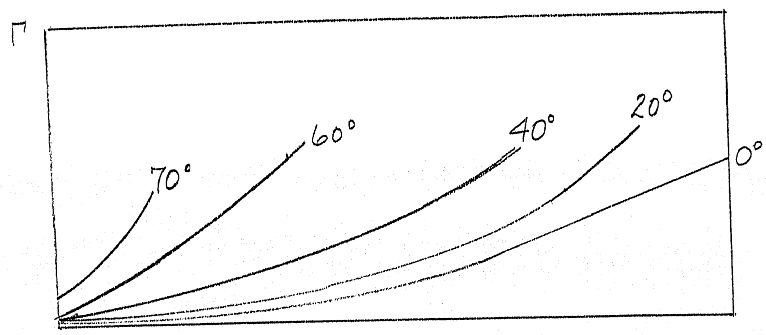

Figure 3. Absorption coefficients on passage through the E layer. $f_{kp} = 4 \times 10^6$ cycles (triangular law)

Since we still have only incomplete data on the variation of ionization with altitude, in constructing a theory of the absorption of radio waves we must take a law of variation of ionization that agrees fairly well with the experimental data.

We calculated the coefficients of absorption for both normal and oblique incidence of a ray on the layer, on the basis of the well-known theorem of Martyn [4]. We considered two basic cases of radio-wave absorption: (1) absorption on passage of radio waves through the ionized layers (D, E, and F_1), and (2) absorption on reflection of radio waves from the ionized layers (E, F_1 and F_2).

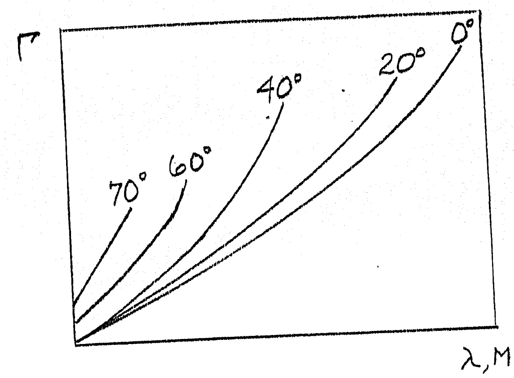

Figure 4. Absorption coefficients on passage through the E layer.
$f_{kr} = 3 \times 10^6$ cycles (triangular law).

The curves presented on Figure 2 characterize the dependence of absorption on wave length (for varying angles of incidence) in the case of passage of the waves through the D layer, at $N_{max} = 10^3$ el/cm^3 and $p_0 = 10^7$ per second. Since in this case the absorption coefficient Γ is directly proportional to N_{max}, the curves presented may be used for any values assumed for the ionization of the D layer, with corresponding changes in the scale of the ordinate axis.

For the D layer, in which the index of refraction of short waves may be considered as equal to unity, the absorption coefficient for oblique incidence will be equal to the absorption coefficient for normal incidence multiplied by sec φ, where φ is the angle of incidence of the ray on the layer.

Figures 3 and 4 give the analogous curves for passage of waves throughthe E layer at two values of the critical frequency (f_E = 4 megacycles, f_E = 3 megacycles).

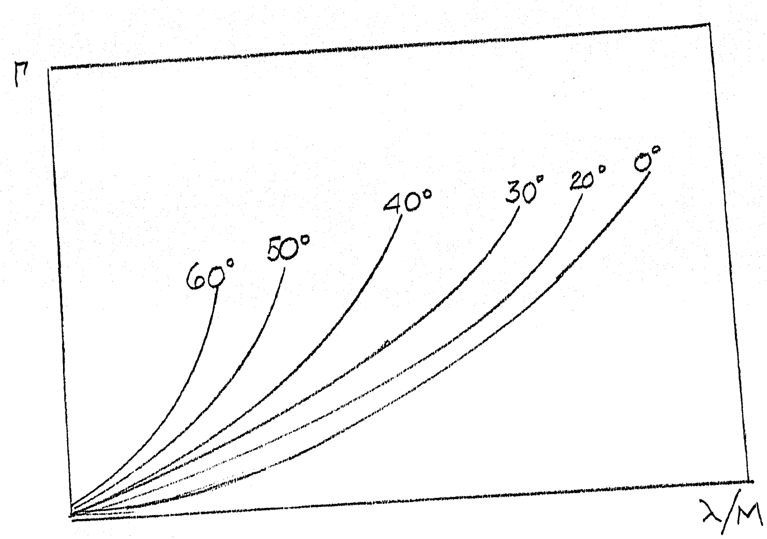

Figure 5. Absorption coefficients on passage through the E layer.

$f_{kp} = 3 \times 10^6$ cycles (parabolic law)

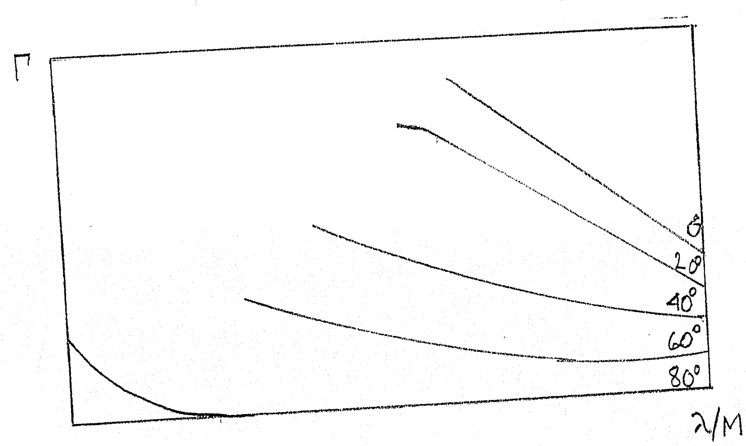

Figure 6. Absorption coefficients on reflection from the E layer.

$f_{kp} = 4 \times 10^6$ cycles (triangular law).

The curves are plotted for the number of collisions $p_0 = 2 \times 10^5$ per second; however, by virtue of the direct proportionality between Γ and p_0, these curves may be used for any assumed number of collisions in the E layer, with corresponding change of scale.

The curves on Figures 2, 3 and 4 are calculated for the so-called "triangular" law for the distribution of ionization by altitude (linear increase in ionization as altitude h increases from zero to h_m, and then linear decrease as altitude further increases from h_m to $2h_m$).

Figure 5 gives the analogous curves for the E layer (with f_E = 4 megacycles), calculated by a parabolic law of variation in ionization with altitude.

We see that the absorption of radio waves on passage through an ionized layer will be the greater, the longer the wave, or in other words, the lower the frequency. The absorption losses also increase with the angle of incidence of the ray, inasmuch as the path of the ray through the ionized layer becomes longer.

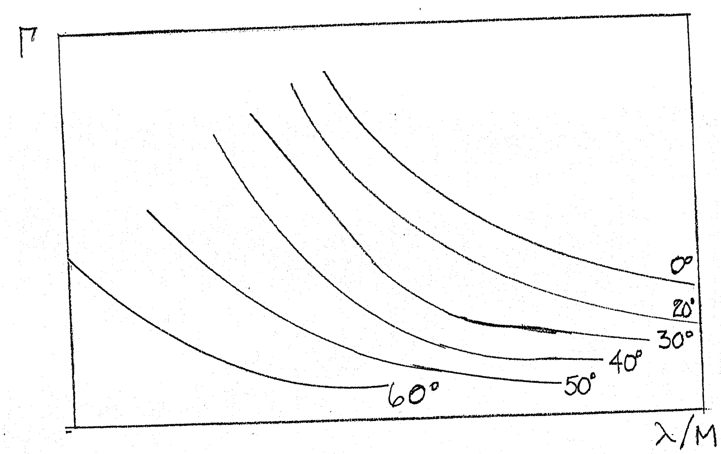

Figure 7. Absorption coefficients on reflection from the E layer. $f_{kp} = 4 \times 10^6$ cycles (parabolic law)

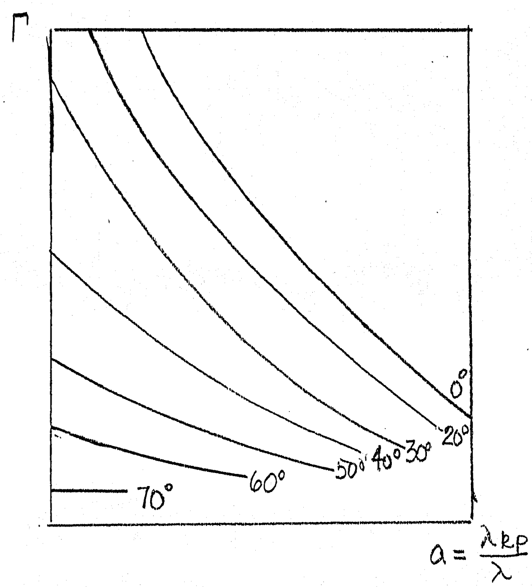

Figure 8. Absorption coefficients on reflection from the F_2 layer.
$f_{kp} = 5.7 \times 10^6$ cycles (triangular law)

Figures 6 and 7 give curves that characterize the dependence of absorption on wave length for the case of reflection of radio waves from the E layer, using the triangular and parabolic laws of variation of ionization with altitude, respectively. Figure 8 gives analogous curves for the F_2 layer ($f^0_{F_2} = 5.7$ megacycles). We see that the absorption losses for reflection of a ray from the layer decline with increasing wave length. This phenomenon is explained by the fact that as wave length increases the depth of penetration of the layer by the wave decreases, although the absorption per unit length of its path increases.

This reduction in the length of the path traversed by the ray through the ionized layer also accounts for the decline in absorption with increasing angle of incidence of the ray on the layer.

Our calculations of the absorption coefficients, and the curves plotted from these calculations, make it possible to make a more detailed analysis of certain very important questions connected with the absorption of radio waves. These questions include (1) elucidation of the relative roles played by the several layers in the absorption of radio waves, and (2) elucidation of the dependence of the absorption coefficients on frequency.

These questions will be considered separately.

THE RELATIVE ROLES PLAYED BY THE SEVERAL IONIZED LAYERS IN THE ABSORPTION OF RADIO WAVES

Analysis of the number of collisions in the several ionized layers leads us to the conclusion that the lower, D and E, layers of the ionosphere probably play the principal part in the absorption of radio waves. Absorption in the F_1 and F_2 layers is considerably less than in the layers below. Therefore the absorption in the F region may be neglected in a good many cases in making approximate calculations for the daylight hours.

However, by virtue of the peculiarities in the mechanism of the collisions in the F_2 layer, the absorption of radio waves at reflection from this layer is not negligibly small in comparison to the absorption in the lower layers. When a ray falls vertically on this layer (or at small angles of incidence), the absorption in the F_2 layer, in high-frequency work, is entirely commensurable with that in the lower layers, even during daylight hours. In the nighttime, however, the absorption in the F_2 layer at relatively high frequencies not infrequently dominates the absorption in the remaining E layer.

The greatest interest of all attaches to the elucidation of the relative roles played by the D and E layers, which are primarily responsible for the absorption. Various conflicting opinions may be found in the literature on this point. Thus, in the American manual on the propagation of radio waves [13] and in the work of Raver [2], only the absorption in the D layer is considered; the absorption in the other layers, including that in the E layer, is not taken into consideration. A. N. Shchukin [14] points out the importance of the D layer. On the contrary, Martyn [4] takes account only of the absorption in the E layer. White and Straker [15] assign the primary importance to the E layer. They express themselves as follows on this subject: "Although other regions of ionization (for instance the D region) are occasionally encountered below the E, it still remains to be proved that they possess a fairly constant form and contribute a share of the total absorption."

To elucidate the proportionate roles of the several layers that follow from the absorption coefficients calculated by us, we calculated the absorption in each of the ionized layers, together with total absorption, in relation to the distance, at varying wave lengths and at various seasons.

Let us consider, for example, the curves that characterize the dependence of the absorption of radio waves on the distance, at wave length 100 meters, for daytime in summer (Figure 9). The reflection takes place from the E layer. We present the curves for absorption in the D and E layers separately, and also the curve of total absorption. The absorption in the D layer increases with the distance, i.e. with the angle of incidence of the ray on the layer; while on the contrary absorption at reflection of the waves from the E layer falls with increasing distance. Therefore the total absorption falls at first as the distance increases, reaches a minimum at a certain distance, and then begins to rise as the distance continues to increase. We see here that the relative role of the absorption at reflection from the E layer falls with increasing distance, while the relative role of the absorption in the D layer increases; at distances of 500 kilometers and over, the absorption in the D layer dominates that in the E layer under any and all circumstances.

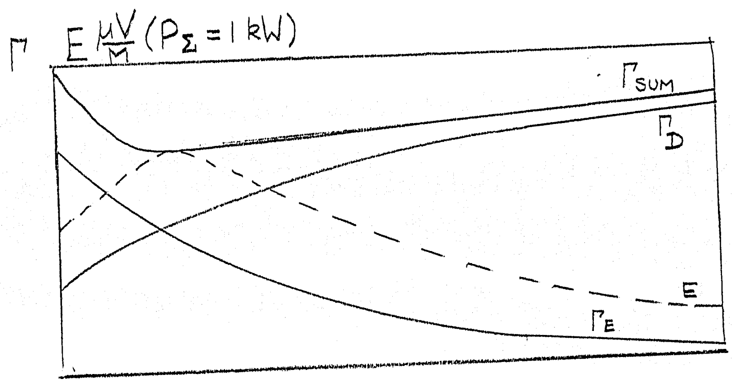

Figure 9. Absorption coefficients and field strength. Summer, 12 hours. 100 meters

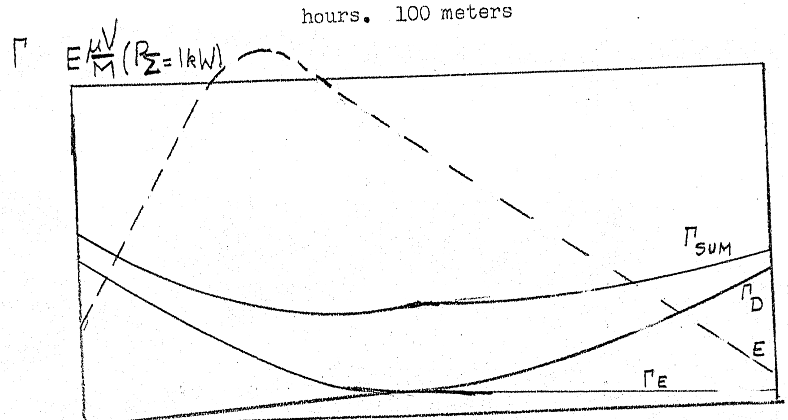

Figure 10. Absorption coefficients and field strength. Winter, 12 hours. 100 meters

Figure 11 shows the variation in absorption with distance, for a 50-meter wave, on a summer day. Reflection from the E layer begins at a distance of 300 kilometers. On comparing the absorption curves for this wave length with the corresponding curves for wave length 100 meters, we see that the D-layer absorption is considerably lower for wave length 50 meters. Therefore, even though absorption in the D layer increases with increasing distance, while that in the E layer falls, the dominance of the E layer commences only at relatively great distances.

Figure 12 shows the absorption curves of radio waves for daytime in summer at operating wave length of 30 meters. Reflection occurs from the F_2 layer. Here our attention is struck by the circumstance that at relatively small distances (400 - 600 kilometers) the absorption in the F_2 layer on reflection of the wave from it dominates the absorption in the D and E layers (on passage of the waves through them).

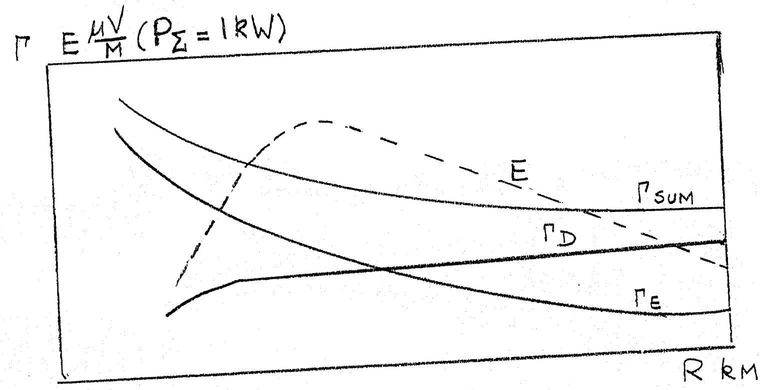

Figure 11. Absorption coefficients and field strength. Summer, 1200 hours. 50 meters

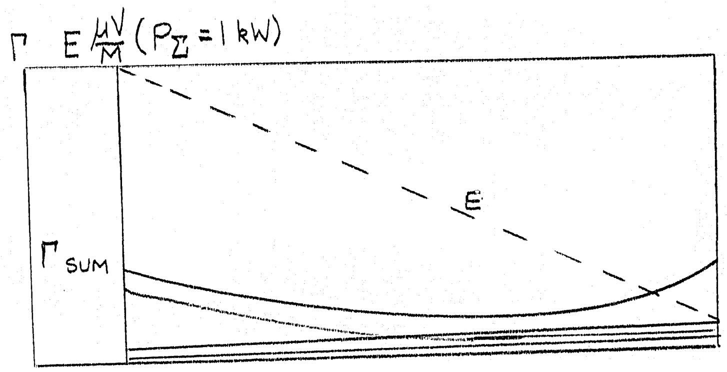

Figure 12. Absorption coefficients and field strength. Winter, 1200 hours. 30 meters

Recapitulating what has been said on the relative roles of the several layers in the absorption of radio waves, we reach the following conclusions.

1. It is necessary to take into account the absorption in both D and E layers. The relative importance of these layers may vary according to frequency, angle of incidence (otherwise expressed as distance), season and time of day.

2. The role of the F_1 layer, which is confined to the daytime of the summer months, is slight in comparison to the lower layers, both for passage of radio waves through it and for their reflection from it, except for cases where the working frequency is very near the critical frequency of this layer.

In approximate calculations the absorption in the F_1 layer may be disregarded.

3. The absorption in the F_2 layer is as a rule considerably

less than that in the D and E layers; but it cannot always be neglected. Thus, for relatively high frequencies at small angles of incidence, and also during the nighttime, absorption in the F_2 layer may dominate absorption in the lower layers.

THE RELATIONSHIP OF ABSORPTION COEFFICIENTS TO FREQUENCY

I. We shall first consider the several ionized layers from the point of view of the dependence of the absorption coefficients on the frequency.

1. The D layer. If we take the effective number of collisions at the lower boundary of the D layer as equal to 10^7, then for frequencies of 3 megacycles and higher the value of p^2 may be neglected by comparison with ω^2. Taking into consideration the fact that the index of refraction for the D layer is close to unity, we find that the aggregate coefficient of absorption in this layer, for vertical incidence of the ray and the "triangular" law of distribution of ionization by altitude, may be determined by the following formula [12]:

$$\Gamma_1 = \frac{P_q H^2}{c h_o}\left[1 - e^{\frac{h_M}{H}}\left(1 + \frac{h_M}{H}\right)\right] \qquad (5)$$

and

$$\Gamma_2 = \frac{P_o H^2}{c h_o}\left[e^{-\frac{2h_M}{H}} - e^{-\frac{h_M}{H}}\left(1 - \frac{h_M}{H}\right)\right] \qquad (6)$$

where Γ_1 is the absorption in the lower region of the layer (up to the maximum of absorption), and Γ_2 is the absorption in the upper region;

$$h_0 = \left(\frac{\omega}{\omega_{kr}}\right)^2 h_M, \tag{7}$$

$$\Gamma = \Gamma_1 + \Gamma_2 = \frac{p_0 H^2}{c a^2 h_M}\left(1 - e^{-\frac{h_M}{H}}\right)^2 \tag{8}$$

By analogy we obtain, for a parabolic law of ionization distribution the following equation:

$$\Gamma = \frac{2p_0 H^2}{c a^2 h_M}\left[\left(1 - \frac{H}{h_M}\right) + e^{-\frac{2h_M}{H}}\left(1 + \frac{H}{h_M}\right)\right], \tag{9}$$

where

$$a = \frac{\omega}{\omega_{kr}}$$

We thus see that for $p_0 = 10^7$ per second the absorption in the D layer (for frequencies above 3 megacycles) should be inversely proportional to the square of the frequency.

At frequencies lower than 3 megacycles, the increase in absorption as the frequency declines is appreciably slowed, since the number of collisions p is of the same order as the frequency of vibration.

It must, however, be carefully noted that we have here considered the absorption in the D layer at a certain effective electron density N and a certain effective number of collisions p. In fact, as we have already pointed out, two different types of absorption take place in the D layer, one due to the collisions between electrons and molecules and the other due to collisions between ions and molecules. The effective number of collisions, and therefore also the frequency dependence, will be different for these two types of absorption.

To illustrate, let us consider the curves of "ion" type absorption, of "electron" type absorption, and of aggregate absorption (without taking the earth's magnetic field into account) in relation to wave length, which are presented in Figure 13. The curves are calculated for a total effective electron density $N = 4 \times 10^3$ el/cm^3, under the assumption that the actual electron density $N_e = 4 \times 10^2$ el/cm^3, and all of the remainder is attributable to ion density converted to the equivalent electron density.

Γ_{total} without allowing for the earth's magnetic field

Γ_{el} without allowing for the earth's magnetic field

Γ_{total}(- - -) allowing for the earth's magnetic field

Γ_{el} allowing for the earth's magnetic field

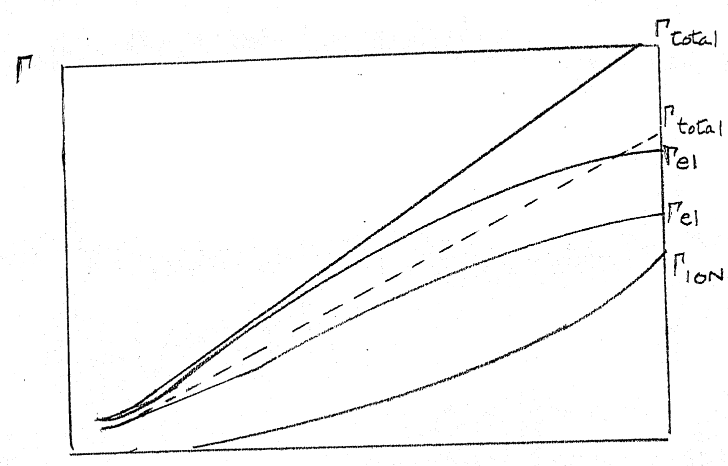

Figure 13. Absorption coefficients in the D layer

$N_{calc} = 4 \times 10^3$ el/cm^3; $N_e = 4 \times 10^2$ el/cm^3

The number of collisions p_0 is taken at 5×10^7 per second for the electrons, and 5×10^5 per second for the ions. Since in the latter case $p^2 \ll \omega^2$, the absorption of "ion" type is inversely proportional to the square of the frequency. In consequence of the higher effective number of collisions for electrons, the absorption of the "electron" type manifests a less pronounced frequency dependence. Thus when the wave length is increased from 15 to 75 meters (i.e. when the frequency varies from 20 to 4 megacycles) the absorption Γ_{el} increases 15 times, instead of 25 times by the law of squares. In this band, the mean variation of Γ_{el} is inversely proportional to $f^{1.7}$. For a variation of the wave length from 75 to 150 meters (4 - 2 megacycles), Γ_{el} doubles, i.e. its variation is inversely proportional to the first power of the frequency.

It follows from a consideration of the aggregate absorption curve that in this case the frequency dependence approaches somewhat closer to a square variation than the dependence obtained for the absorption of purely "electron" type.

Thus on taking account of the mechanism of absorption of the energy of radio waves in the D layer, we come to the conclusion that the frequency dependence of absorption is, taken as a whole, lower than a square variation, but does not differ very greatly from it for the band of relatively high frequencies ($f > 4$ megacycles). For lower frequencies this dependence approaches the linear.

We must turn our attention to the circumstance that, although we have assumed, in this numerical calculation, that the actual electron density is only 10 percent of the total equivalent electron density, nevertheless the absorption of the "electron" type plainly dominates that of the "ion" type as a result of the far higher effective number of collisions in the former case than in the latter.

It must also be noted that variation in the percentage ratio between the actual electron density and the ion density, converted to the equivalent electron density, may result in considerable variation of the absorption of radio waves in the D layer and exert a certain influence on the frequency dependence of this absorption.

The freeing of a considerable number of electrons associated with the molecules of the gas, that is, the redistribution between the number of electrons and the number of negative ions, may result in an anomalous increase in the absorption in the D layer.

II. The E layer. For the E layer, we may consider that $p^2 \ll \omega^2$; then the absorption coefficient

$$\gamma = \frac{2\pi\sigma}{cn} = \frac{2\pi p N e^2}{cm\,\omega^2\sqrt{1 - \frac{4\pi N e^2}{m\omega^2}}} \qquad (11)$$

and the aggregate absorption on the path S

$$\Gamma = \int_S \gamma\, ds = \frac{2\pi e^2}{cm\,\omega^2} \int_S \frac{pN}{\sqrt{1 - \frac{4\pi N e^2}{m\omega^2}}}\, ds \qquad (12)$$

Consequently when radio waves pass through the E layer, the absorption in it will be inversely proportional to the square of the frequency and vary even more sharply than that, since the index of refraction n can no longer be considered equal to unity for the E layer; the value of this index falls with the frequency.

When radio waves are reflected from the E layer (at frequencies which are not very close to the critical frequency) the aggregate absorption in this layer, for vertical incidence and the "triangular" law of ionization distribution, may be calculated by the formula

$$\Gamma = \frac{4}{3}\frac{p_o h_o}{c}\left[1 - \frac{4}{5}\frac{h_o}{H} + \frac{12}{35}\left(\frac{h_o}{H}\right)^2 - \frac{32}{315}\left(\frac{h_o}{H}\right)^3 + \frac{3}{130}\left(\frac{h_o}{H}\right)^4 - \frac{1}{235}\left(\frac{h_o}{H}\right)^5 \ldots\right]. \tag{14}$$

The analogous formula has been derived for us for the parabolic law as well [12]. It is not difficult to see that the absorption in the case of reflection of waves from the layer will fall with the frequency.

The numerical expression of this regularity depends on the ratio between the working frequency and the critical frequency of the layer.

3. The F_1 layer. Inasmuch as the mechanism of absorption in the F_1 layer should be considered the same as that in the E layer, while the inequality $p^2 \ll \omega^2$ in unconditionally and under all circumstances true for the F_1 layer, it follows that all that has been said about the frequency dependence of absorption in the E layer is equally applicable to the F_1 layer as well.

4. The F_2 layer. We consider the absorption in the F_2 layer only for the case of the reflection of radio waves. By virtue of the peculiarities in the mechanism of absorption in the F_2 layer, we assume, in the first approximation, as has already been said, that the number of collisions p does not vary with altitude.

In that case, we obtain, as the linear law of variation of ionization with altitude:

$$\Gamma = \frac{4}{3} \frac{p h_0}{c} = \frac{4}{3} \frac{p h_M}{c} \left(\frac{\omega}{\omega_{Kr}}\right)^2. \qquad (15)$$

Consequently the absorption will be directly proportional to the square of the frequency.

For the parabolic law

$$\Gamma = \frac{p h_M}{2ca} \left(\frac{a^2+1}{2} \ln \frac{1+a}{1-a} - a\right),$$

where $a = \frac{\omega}{\omega_{kp}}$

This formula also expresses the sharp increase in absorption as the frequency rises.

Thus when we consider the frequency dependence of absorption in the several layers, we reach the following conclusions:

a. The frequency dependence of absorption in the D layer is determined to a considerable extent by the effective number of collisions per second, and also by the ratio between the volume density of electrons and that of ions. At higher frequencies (the short-wave band proper) the absorption in this layer is, roughly, inversely proportional to the square of the frequency. In the intermediate wave-band this dependence appreciably slackens and approaches inverse variation as the first power of the frequency.

b. On passage of a ray through the E and F_1 layers, the absorption in them is inversely proportional to the square of the frequency or may even vary more sharply than that.

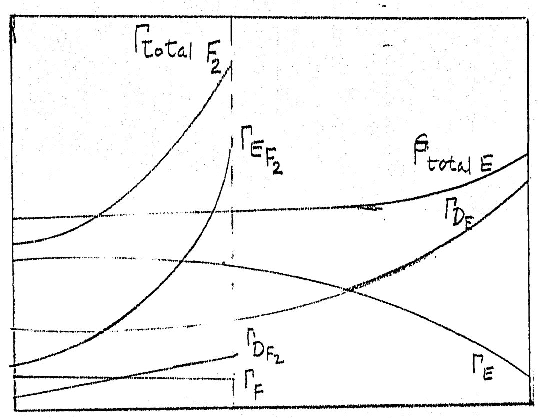

Figure 14. Absorption coefficients. Summer, 1200 hours.

R = 400 kilometers

c. For the case of reflection of the ray from the layer, the absorption in general falls off as the frequency is reduced. Specifically, the absorption in the F_2 layer may be considered to be approximately directly proportional to the square of the frequency.

II. Let us now consider the dependence of the total absorption on the frequency under the actual conditions of propagation of radio waves over different distances and at different seasons and hours of the day.

We shall separately discuss the cases of reflection from the E layer and from the F region (the F_1 and F_2 layers).

1. Reflection from the E layer. Figure 14 shows curves that characterize the dependence of absorption on frequency when a ray passes through the D layer and is reflected from the E layer, as well as the curve for aggregate absorptions for daylight in summer

(1200 hours) over a distance of 400 kilometers. We see that absorption in the D layer increases with declining frequency, while absorption in the E layer decreases. Consequently the aggregate absorption in a certain frequency band (6 - 3 megacycles) varies very slightly with varying frequency. At frequencies under 3 megacycles the aggregate absorption commences to grow appreciably with declining frequency, in consequence of the fact that absorption in the D layer begins definitely to dominate over that in the E layer.

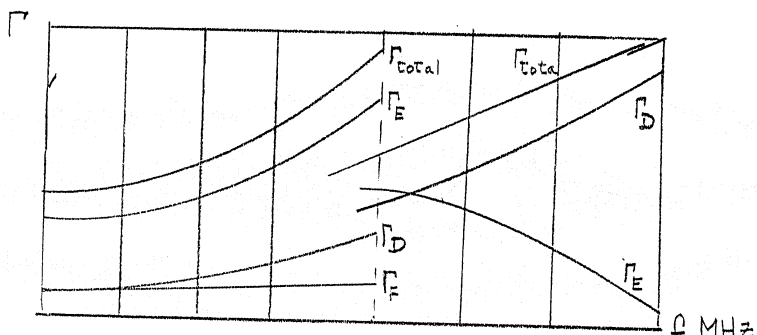

Figure 15. Absorption coefficients. Summer, 1200 hours.

R = 1000 kilometers

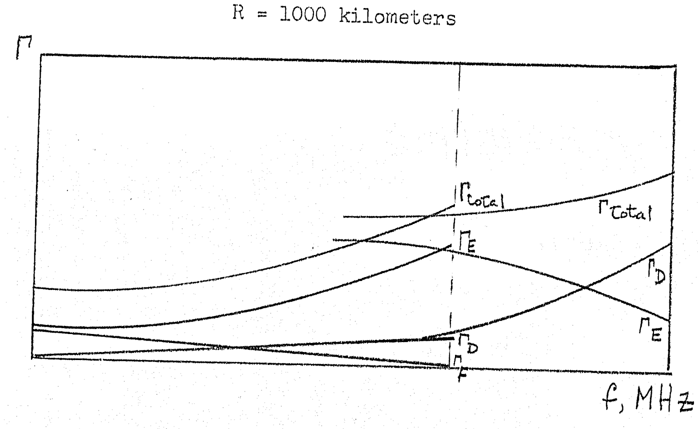

Figure 16. Absorption coefficients. Winter, 1200 hours.

R = 1000 kilometers

In Figure 15 the analogous curves for a summer noon and a distance of 1000 kilometers are plotted at the right. We see that the aggregate absorption in the D and E layers combined clearly grows with declining frequency, with an average variation inversely proportional to $f^{0.75}$.

An interesting curve of aggregate absorption is obtained for summer noon at a distance of 1500 kilometers (Figure 17). This curve has a minimum around a frequency of 8 megacycles. At lower frequencies absorption appreciably increases with declining frequency. As frequency falls from 6 to 3 megacycles, the absorption doubles, that is, it is here inversely proportional to the first power of the frequency.

At frequencies over 8 megacycles, on the contrary, there is a certain increase in the absorption as frequency increases, owing to the increasing absorption on reflection from the E layer.

2. Reflection from the F region. On Figure 14, at the left, the absorption curves are plotted for the reflection of waves from the F layer. The absorption on passage of the ray through the E layer is dominating here. For this reason the absorption definitely grows with lowered frequency (increasing 1.5 times with change in frequency from 6 to 4.5 megacycles).

We see an analogous picture on Figure 15 (summer day, distance 1000 kilometers). The aggregate absorption on reflection from the F layer, which is primarily determined by the losses in the E layer, grows as the frequency declines (by approximately 2.5 times when the frequency passes from 10 to 6 megacycles, i.e. almost inversely proportional to the square of the frequency).

Figure 18 shows absorption curves for a winter day (R = 1500 kilometers). At relatively high frequencies the waves are reflected from the F_2 layer. The aggregate absorption, just as in the preceding case, is markedly increased with declining frequency, rising by approximately 2.6 times as the frequency drops from 10 to 6 megacycles, or almost inversely proportional to the square of the frequency.

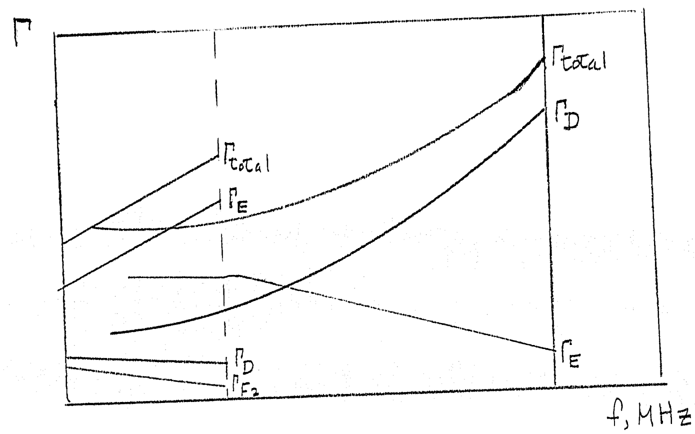

Figure 17. Absorption coefficients. Summer, 1200 hours.

R = 1500 kilometers

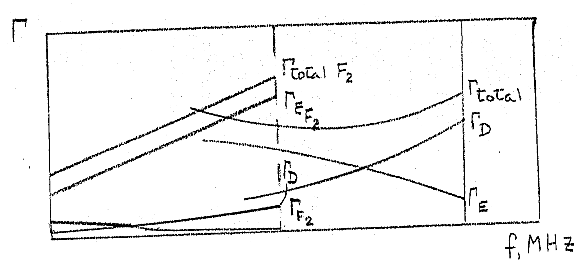

Figure 18. Absorption coefficients. Winter, 1200 hours.

R = 1500 kilometers

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We see a somewhat different frequency dependence in Figure 16, on which the absorption curves for a winter day at a distance of 1000 kilometers have been plotted. In this case, at the relatively high frequencies of 10 - 7 megacycles, the aggregate absorption varies but slightly with the frequency, since the absorption on reflection from the F_2 layer, which falls as the frequency falls, is here of the same order as the E-layer absorption. At lower frequencies the aggregate absorption perceptibly increases.

We see an interesting picture in Figure 19, which shows the absorption curves for a winter night (R = 400 kilometers). Absorption occurs in this case on passage of the waves through the remaining E layer (for which we take the critical frequency as 0.5 megacycle) and on reflection from the F_2 layer. For shorter waves the latter type of absorption prevails, for longer waves, the former type. When frequency is reduced, the absorption falls at first, to reach a minimum around f = 2.5 megacycles, after which it begins to increase again.

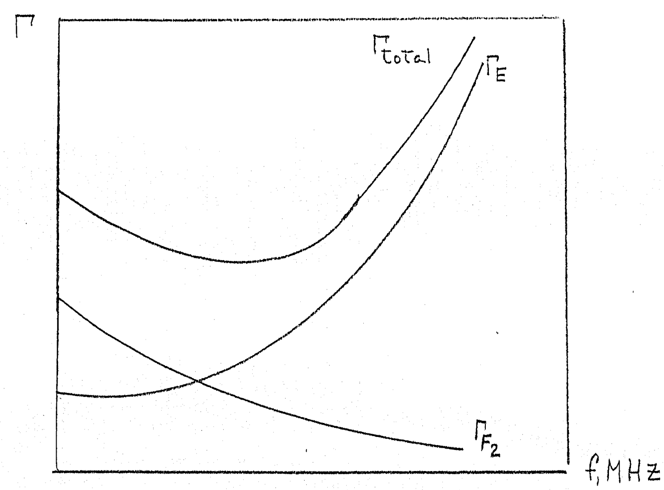

Figure 19. Absorption coefficients, winter, 2400 hours.

R = 400 kilometers

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On the basis of what has been said on the frequency dependence of the aggregate absorption, the following conclusions may be drawn:

a. In view of the fact that the frequency dependence of absorption is completely different for the case of the passage of the ray through the layer and for that of its reflection from the layer, while the role of the several layers in absorption is by no means the same, the frequency dependence of absorption, under the actual conditions of radio-wave propagation, is determined according to which of the layers reflect the rays and what the angle of incidence is of those rays on one layer or another.

It is therefore impossible to indicate any universal frequency dependence for the absorption of radio waves throughout the entire path of the ray in the ionosphere, as has been done by certain authors.

b. For the case of reflection from the E layer, the absorption as a rule varies more slowly with the frequency than it does when reflected from the F layer, since in the former case the aggregate increase in the absorption as the frequency is diminished is checked by the reduction of the absorption in the E layer. When reflection takes place instead from the F layer, this retardation of the increase in absorption, as frequency falls, is considerably less effective. In other cases, however, (for example at relatively high frequencies with small angles of incidence, and likewise during the nighttime) this variation proceeds much more slowly. During the nighttime the absorption of radio waves on reflection on the F_2 layer may dominate that in the residual E layer, and in that case the aggregate absorption may grow with increasing frequency.

III. Let us now analyze the influence of the earth's magnetic field on the frequency dependence of the absorption coefficients. We consider, as is usually done, the two limiting cases of the propagation of radio waves with respect to the direction of the earth's magnetic field: (a) longitudinal propagation and (b) transverse propagation.

For the case of longitudinal propagation, the coefficient of absorption has the form

$$\gamma = \frac{p}{2ch} \frac{f_0^2}{(f \pm f_L)^2}, \tag{17}$$

where

$$f_0 = \sqrt{\frac{Ne^2}{\pi M}} \tag{18}$$

is the critical frequency of reflection from the given level of ionization N, and f_L is the gyrofrequency corresponding to the component of the earth's magnetic field that is parallel to the direction of propagation of the radio waves. A positive sign in the expression for gamma corresponds to the ordinary component of the wave, while a negative sign corresponds to an extraordinary component. For transverse propagation, the ordinary component

$$\gamma = \frac{p}{2cn} \frac{f_0^2}{f^2}, \tag{19}$$

and the extraordinary component is represented by

$$\gamma = \frac{p}{2cn} f_0^2 \frac{f^2 + f_T^2}{f^2 - f_T^2}, \tag{20}$$

where f_T is the gyrofrequency corresponding to the component of the earth's magnetic field perpendicular to direction of propagation of the radio waves.

Since the component which experiences the least amount of absorption is of the most interest to us, we shall henceforth consider the ordinary component. We shall therefore write the coefficient of absorption in the following form:

$$\gamma = \frac{p}{cn} \frac{f_o^2}{(f+f_L)^2} \tag{21}$$

for longitudinal propagation, and

$$\gamma = \frac{p}{cn} \frac{f_o^2}{f^2} \tag{22}$$

for transverse propagation.

It is possible to show from the general formulae that determine the dielectric permeability of a medium for the case of propagation of radio waves through an ionized gas, and allowing for the influence of the earth's magnetic field [2, 16], that the case of approximation towards longitudinal propagation is determined by the inequality

$$(f-f_o)^2 \gg \frac{f^2 f_c^2}{(f+f_o)^2} \tag{23}$$

while the case of approximation to transverse propagation is determined by the inequality

$$(f-f_o)^2 \ll \frac{f^2 f_c^2}{(f+f_o)^2}, \tag{24}$$

where

$$f_c = \frac{\sin^2\theta}{2\cos\theta} f_H \qquad (25)$$

f_H is the gyrofrequency, and θ is the angle between the direction of propagation of the radio waves and the direction of the earth's magnetic field.

It is very important to know, in calculating the coefficients of absorption, when we have in practice an approximation to longitudinal propagation ("quasilongitudinal approximation") and when we have an approximation towards transverse propagation ("quasitransverse approximation").

The graph in Figure 20 serves to answer this question, and has been constructed from an analysis of the inequalities presented above.

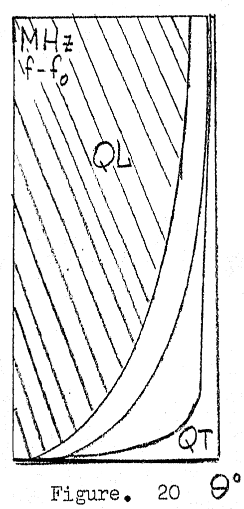

Figure. 20

The hatched portion of the graph, on the left side, represents the region where the inequality that determines quasilongitudinal approximation is unconditionally and under all circumstances true, while the hatched portion to the right represents the region where the inequality for quasitransverse approximation is unconditionally and under all circumstances satisfied. The condition that the corresponding part of one inequality shall be at most 9 times larger than that of the other serves here as a measure of approximation.

The curve produced between the hatched areas determine a line of demarcation, for which the inequalities (23) and (24) above presented are transformed into an equality.

We see from the graph in Figure 20 that for the case of the passage of the radio waves through a layer $(f > f_o)$ the inequality that determines the quasi-transverse approximation will be true only for angles near $\frac{\pi}{2}$, while the region for which the quasilongitudinal approximation holds is far more extensive.

For this reason, for the case of the passage of radio waves through a layer, the formula

$$\gamma = \frac{p}{2cn} \frac{f_o^2}{(f+f_L)^2} = \frac{2\pi}{cn} \frac{pNe^2}{m(\omega+\omega_L)^2}. \quad (26)$$

has the greatest practical significance.

Since it would be extremely tedious (especially where there is more than one reflection) to take into account the exact value of f_L, which will depend on the geomagnetic latitude and the direction of radio wave propagation, it is recommended [2] that $f_L = 1,2$ MHz be taken as a rough approximation for median latitudes.

For random reflection of radio waves from a given level of ionization ($f = f_0$) a quasi-transverse approximation will take place.

For the usual component we must then use the following formula:

$$\gamma = \frac{p}{2cn} \frac{f_0^2}{f^2} = \frac{2\pi}{cn} \frac{pNe^2}{M\omega^2}, \qquad (27)$$

Strictly speaking, however, it would hold only for the very limited region in which reflection occurs (with the working frequency f close to f_0).

In practice we will have, for example, a case of quasi-transverse approximation, in which the working frequency of the layer and the reflection of the wave takes place at a very short distance from its lower boundary.

If, however, the wave, before being reflected from that level, traverses a considerable path in the reflecting layer, with the difference ($f - f_0$) great enough in the lower part of that path, then we will have a case of quasilongitudinal approximation in this sector, which approximation will then pass over into a case of quasitransverse approximation as the difference ($f - f_0$) approaches zero.

The practical allowance for the influence of the earth's magnetic field on the frequency dependency of absorption in this more complicated case of wave reflection requires further elaboration.

It is extremely important to solve the question as to precisely the ionized layers in which the influence of the earth's magnetic field on absorption should be taken into account. Allowance must obviously be made for this influence in the case where the wave traverses the E and F_1 layers, since, in accordance with what has been said above, the absorption in these layers is primarily determined by the collisions of electrons with neutral molecules and to some extent with ions as well.

The question of the influence of the earth's magnetic field on absorption in the D layer is far more complicated, since absorption here is due in part to collisions of electrons, and in part to collisions of ions, with neutral molecules. Obviously a correction for the influence of the earth's magnetic field should be introduced into the calculations of absorption of the first type, and obviously it would not be rational to introduce such a correction into the calculations for absorption of the second type.

In Figure 13, which we have considered earlier in this paper, there is a curve characterizing the dependence of absorption of the "electron" type on wavelength, allowing for the influence of the earth's magnetic field, as well as a curve of aggregate absorption for this case (no allowance for the influence of the earth's magnetic field is made with the absorption of "ion" type). Consideration of this curve shows that the absorption in the band from 15 to 75 meters (20 to 4 megacycles) is approximately inversely proportional to $(f+f_L)^2$.

This approximate frequency dependence may thus be assumed to hold the case of passage of short waves through the D layer.

ELECTRIC FIELD STRENGTH AT THE POINT OF RECEPTION

The strength of the electric field at the point of reception may be determined as follows:

$$E = E_0 e^{-\int_S \gamma \, ds} = E_0 e^{-\Gamma}, \tag{28}$$

where E_0 is the field strength that would be obtained at the point of reception in the absence of absorption (the "unabsorbed" field); $\int_S \gamma \, ds = -\Gamma$ the aggregate coefficient of absorption on all paths of a ray in the ionized layers of the atmosphere.

Let us first consider the question of the calculation of E_0. In determining the non-absorbed field strength of a space wave, Fresnel's coefficient for the reflection of a ray from a surface of the earth that possesses finite conductivity must be taken into account.

In the American manual for radio-wave propagation [13], curves are given for determining field strength as a function of distance. For this purpose, the field strength of a space wave is considered as the strength of a field created by an antenna on an ideally conducting earth

$$E_0 \frac{mV}{M} = \frac{300\sqrt{P_\Sigma kW}}{R^{kM}} \tag{29}$$

multiplied by $\frac{1+|R|}{2}$, where $|R|$ is the modulus of the complex coefficient of Fresnel.

For the case of vertical polarization, Fresnel's coefficient

$$R = \frac{\varepsilon' \cos\varphi - \sqrt{\varepsilon' - \sin^2\varphi}}{\varepsilon' \cos\varphi + \sqrt{\varepsilon' - \sin^2\varphi}}, \tag{30}$$

where φ is the angle of incidence, and ε' is the complex dielectric permeability of the earth

$$\varepsilon' = \varepsilon\left(1 - j\frac{2\sigma}{\varepsilon f}\right). \tag{31}$$

For horizontal polarization,

$$R = \frac{\cos\varphi - \sqrt{\varepsilon' - \sin^2\varphi}}{\cos\varphi + \sqrt{\varepsilon' - \sin^2\varphi}} \tag{32}$$

As the emitter of radiation for distances up to 500 kilometers (the angle between the direction of the emission and the vertical being about 40 degrees or less) we take a half-wave dipole, suspended above the earth at an altitude equal to a quarter of the wavelength, while for distances of over 1000 kilometers, (at an angle of 60 degrees or higher) we take a short vertical vibrator. The field strength for angles of emission from 40 degrees to 60 degrees is interpolated between these two cases.

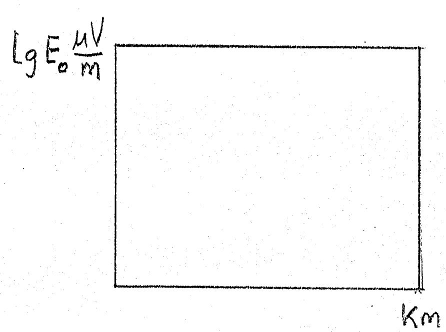

Figure 21. Unabsorbed field strength for frequencies over 4 megacycles.

We made a check of the graphs for unabsorbed field given in the manual, and in the course of that check we eliminated the inaccuracy that consisted of the fact that the American authors took the modulus of Fresnel's coefficient in the multiplier $\frac{1+|R|}{2}$ without allowing for the phase angle. Figure 21 gives the corrected curves of the unabsorbed field at various power levels. The dotted lines show the original curves as given.

By the power P_{Σ} must be understood the radiating power, taking account of the directional action of the antenna employed (the derived power of radiation in a given direction).

Let us turn now to the calculation of the aggregate coefficient of absorption of radio waves in the ionosphere.

The essential peculiarity of the method proposed by us for calculating electric field strength [12, 17] is in the fact that the absorption is first found separately for each of the ionized layers traversed by the ray, and then the aggregate absorption is determined. Thus, if reflection occurs from the F_2 layer, the absorption during passage of the ray through the D, E and F_1 layers is found, together with its absorption on reflection from the F_2 layer. Then the sum of these components is taken. If the reflection is from the E layer, then account is taken of the absorption in the D layer when the ray traverses it, and in the E layer on reflection from it.

Thus the absorption is found on precisely those sectors of the trajectory of the ray in which absorption really takes place.

This is what distinguishes our method from those previously proposed, in which the absorption is considered as uniformly distributed along a calculated path on the earth's surface.

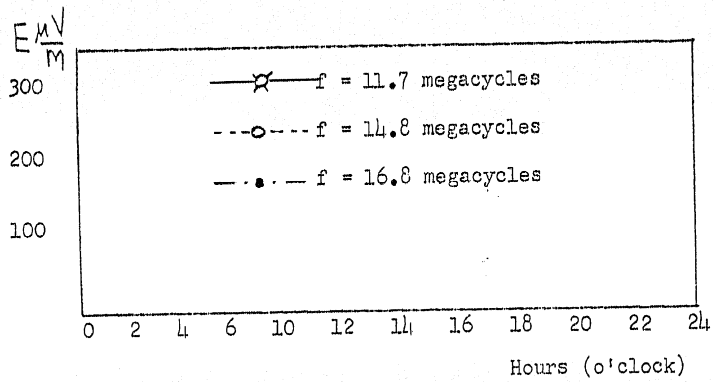

Figure. 22 Field strengths. June 1946

We have calculated the electric field strength in relation to the distance (within the limits of a single skip, for various wavelengths, seasons and times of day. Examples of such calculations are presented in Figures 9 - 12.

For lines of communication having several reflections, the number of reflections is first of all determined, with the limiting distance for a single skip, on reflection from the F_2 layer, taken as equal to $\sim$ 3000 kilometers, or $\sim$ 2000 kilometers if reflected from the E layer.

The absorption for each of the skips is then separately determined (taking geographic latitude into account, together with the time-lag of the points of reflection) and, finally, the aggregate absorption for the entire line of communication.

To illustrate, the calculated curves of field strength are shown for three frequencies in Figure 22. The experimental data are indicated by dots.

Among the partial questions connected with the calculation of the electrical field strength, the question of the dependencies of absorption in the D layer on the sun's altitude above the horizon must be noted.

It follows from Chapman's theory [18] of the so-called "simple layer", produced under the action of uniform solar radiation, that the absorption should be directly proportional to $\cos^{\frac{3}{2}}\chi$ where x is the zenith angle of the sun.

There are however a number of references in the literature to the failure of this theoretical relationship [redacted] to correspond with the experimental data, especially for the ratio between summer and winter absorption. The theoretical relationship gives a ration between the noon coefficients of absorption for summer, winter, at the latitude of England, equal to 6.3, while the measurements made by Appleton [10] give only 2.6 for this ratio. The measurements of White and Brown [19] give the even lower figure of 2.27.

American authors [13] have proposed the following empirical formula for the coefficient, taking into consideration the relationship of absorption to the zenith angle of the sun

$$k = 0.142 + 0.858 \cos x \qquad (33)$$

This formula gives a value of 2.47 for the ratio between the summer and winter coefficients of absorption in England, which agrees well with the above mentioned experimental data.

Analysis of the data on the measurements of absorption coefficients in England as well have lead us to the conclusion that formula (33) agrees far better with the experimental data than does the theoretical formula. For this reason we recommend using the empirical formula mentioned above in calculating the absorption in the D layer.

MINIMUM WORKING FREQUENCIES

Under the conditions of operation of communication lines, the band of working frequencies is limited on the one hand by the so-called maximum working frequency determined by the conditions of reflection for radio waves. Besides the maximum frequency, it is also necessary to know the minimum admissible frequency, that constitutes the lower boundary of the band of working frequencies employed.

The minimum frequency is primarily determined by the absorption of radio waves in the ionized layers of the atmosphere. Although the frequency characteristics of the aggregate coefficients of absorption for the passage of waves through certain ionized layers, depends on a good number of factors, it is still in general possible to consider that the absorption increases as the working frequency decreases.

Consequently for a given distance, a given radiating power of the transmitter, and a given state of ionization, there is a certain frequency (in the short wave spectrum), at which the electric field strength at the point of reception will equal the minimum necessary value. This frequency will then be the minimum working frequency. Let us consider the existing methods of calculating the minimum frequencies that have been proposed by American authors [13] and by Raver [2].

The basic features of the American method are as follows (1) The entire absorption experienced by radio waves in the ionosphere is attributed to the D layer alone: (2) The aggregate absorption along the line of communication is represented in the form of the product $S_0 \bar{k} d$; S_0 being the coefficient of absorption for unit length of the path through that region in which the sun stands directly overhead. The relationship of this coefficient to frequency is given in the form of curves (for frequencies higher than 3 megacycles, S_0 is inversely proportional to the square of the frequency). The influence of the earth's magnetic field is not taken into account; k is the coefficient taking account of the altitude of the sun above the horizon; $\bar{k}$ is its mean value for the line of communication, and is defined only according to its values at the initial and end points of that line; while d is the distance along The great circle.

In order to calculate the minimum frequency, the "unabsorbed field" E_0 is determined, a minimum admissible value for field strength is set, and a frequency is selected at which the value of the field strength shall equal the minimum admissible value. The computations were made by means of nomograms. From the theoretical point of view, this method may be considered as fairly coarse and approximate. Its achievements are apparently embraced in well chosen empirical coefficients. The method of Raver is similar to the American method in that it takes too account only of the absorption in the D layer. The variation of the absorption in dependence on solar altitude is stated to be proportional to $\cos^{3/2} \chi$.

The value P ("Paula"), which represents the absorption at a frequency of 1 megacycle with vertical incidence of the ray and the zenith position of the sun, is of great importance in calculation, as is also the value of B "Berta"), which is equal to $P \cos^{3/2} \chi$.

Raver recommends finding these values experimentally. He considers that the absorption is inversely proportional to $(f+f_L)^2$.

The peculiarity of Raver's method is that it takes account of the focus of a pencil of rays in their successive reflection from the concave surface of the ionosphere and the convex surface of the earth. The calculation of this focus leads to a certain increase in the field strength of the "unabsorbed" ray. Although a certain gain in field strength results from the geometrical consideration of the question of focus, still it seems to us that the introduction of this correction for focus is hardly expedient.

As a matter of fact, the existence of unevenness at the reflecting surfaces (that of the ionosphere and that of the earth), leading to energy losses through dispersion, will probably be enough to reduce to nothing the indicated gain from focus.

The minimum frequency is calculated by the formula

$$f_{MIN} = \sqrt{\frac{B \cdot \cos \gamma}{\delta_{MAX} - \delta_1}} - f_L, \qquad (34)$$

where B is the value of "Berta" above mentioned, γ is the angle of incidence of the ray on the D layer,

$$\delta_{MAX} = \log \frac{E_0}{E_{MIN}}, \qquad (35)$$

E_0 is the field strength at the distance of 1 kilometer, E_{min} is the assigned minimum field strength, and δ_1 is the "space dissipation attenuation", which takes account of the distance factor.

Although Raver's method has a certain advantage in that the minimum frequency is determined by an analytical formula, this advantage is nevertheless based on the inaccurate assumption that all the absorption takes place in the D layer and is subject to a universal frequency dependence.

Let us now consider the basic features of our own method of calculating the minimum frequencies [17].

We write the expression for field strength at the place of reception:

$$E = E_0 e^{-\int_s \gamma \, ds} = E_0 e^{-\Gamma} \qquad (A)$$

In the general case, the absorption coefficient may be represented in the following form:

$$\Gamma = \Gamma_D + \Gamma_E + \Gamma_{F_1} + \Gamma_{F_2}, \qquad (36)$$

where Γ_D, Γ_E, Γ_{F_1}, Γ_{F_2} represent the absorption coefficients in the corresponding layers of the ionosphere. It goes without saying that in specific instances one or more of these components may be absent.

E_0, the unabsorbed field strength, may be determined from the graphs of Figure 21.

To determine the minimum frequency, the minimum allowable field strength at the place of reception must first be set. The minimum field strength depends on the level of atmospheric and industrial interference, on the kind of operation, and on the type of receiving installation. The curves of necessary field strength for various atmospheric zones have been plotted by Potter [13].

Setting the value of $E = E_{min}$, we obtain:

$$E_{min} = E_0 e^{-\Gamma_{MAX}} \tag{37}$$

or

$$\Gamma_{MAX} = \ln \frac{E_0}{E_{min}} \tag{38}$$

where Γ_{MAX} is the maximum allowable absorption corresponding to the minimum allowable field strength.

The frequency for which $\Gamma = \Gamma_{MAX}$ is the minimum working frequency.

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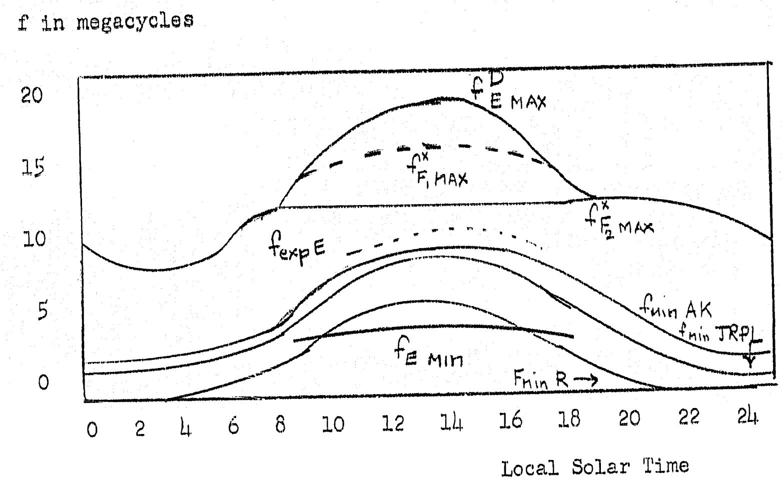

Figure. 23 Maximum and minimum communication frequencies.

Summer 1946

$f_{min}R$: Minimum frequencies calculated by Raver method;

$f_{min}AK$: Minimum frequencies calculated by Kazantsev method;

$f_{min}IRPL$: Minimum frequencies calculated by American method;

$f_{exp}E$: Minimum frequencies at which the F_2 layer is screened by the E layer

The method adopted by us has the advantage of taking into account the absorption not only in the D layer but also in other cases as well, and of not being based on any universal frequency dependence, which, as we have seen, does not in fact exist.

As an example, the curves of maximum and minimum frequencies for two lines of communication are shown in Figures 23-26. These calculations have been made for various seasons of the year.

The minimum frequencies have been calculated by three methods, the American method, the Raver method, and our own method. It is interesting to note that our method and the American give values which are fairly close together for the minimum frequencies (the curves computed by our method being somewhat higher than those of the Americans).

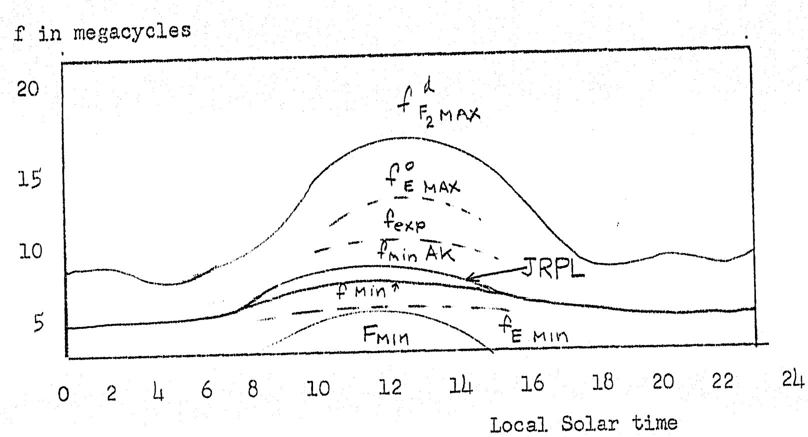

Figure. 24 Maximum and minimum communication frequencies

Winter, 1945/46

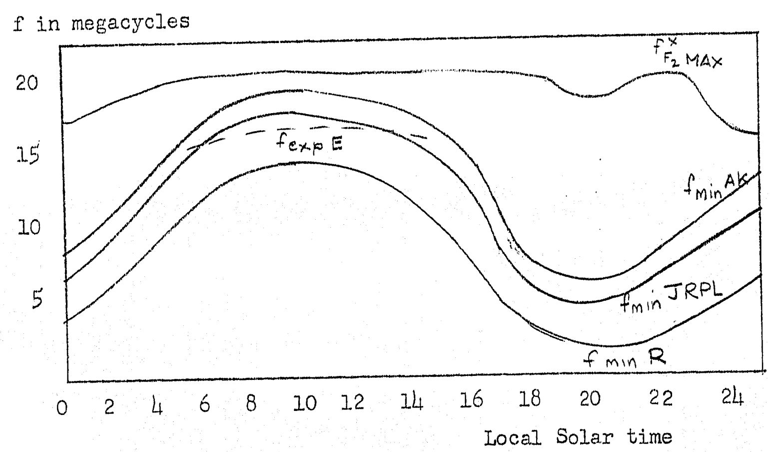

Figure. 25 Maximum and minimum communication frequencies.

Summer 1946

The Raver method gives considerably lower frequencies, especially for the winter. The latter circumstance is explained by Raver's adoption of the theoretical dependence between absorption and the zenith angle of the sun ($\sim \cos^{2/3} x$).

The question of forecasting the minimum working frequencies is very important, as is that of forecasting the electrical field strength for a certain time ahead.

In view of the close connection between the value of the absorption coefficients and the critical frequencies, we use forecasts of the critical frequencies of the E, F_1 and F_2 layers, based on experimental data, as the foundation of our forecasts of the minimum frequencies and the electrical field strength.

Estimation of the variation in the D-layer absorption causes difficulties, since we do not know how the ionization in the D layer varies according to the years of the solar cycle.

We have therefore assumed [17] that the variation here is analogous to that in the adjacent E layer, the origin of which is the same as that of the D layer (ultraviolet radiation).

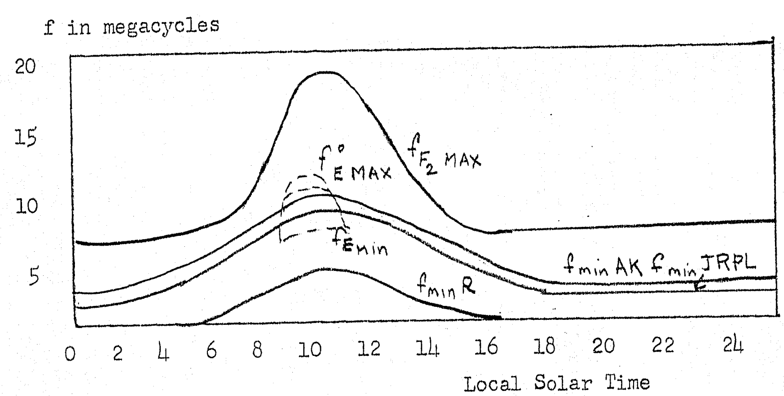

Figure 26. Maximum and minimum communication frequencies. Winter, 1945/46

At the present time we dispose of certain experimental material for testing this assumption, namely the British material on the absorption in the D layer at frequency 1 megacycle (a value analogous to the value of "Berta" used by Raver).

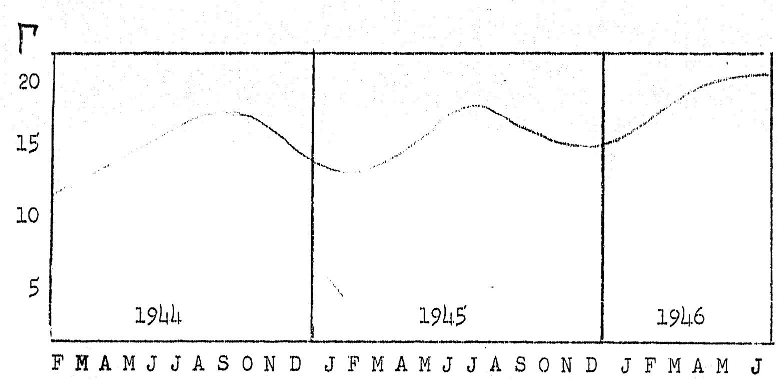

Figure. 27. Mean monthly values for the absorption in the D layer (1 megacycle) at noon

The variation in this absorption, proportional to the ionization N, is shown in Figure 27. The mean value of the coefficient of growth for this magnitude, over the 2 years from 1944 to 1946, is 1.33. The mean value of the coefficient of growth of ionization in the E layer for the same period is ~ 1.4. We thus have a rather good coincidence.

It goes without saying that the theoretical work on the absorption of radio waves and the electrical field strength must be intimately linked with the experimental work.

It seems necessary to us to conduct purposefully organized and extensive experimentation on the measurement of electrical field strength at various frequencies. It is also necessary to organize regular measurements of the coefficients of signal reflection from the ionosphere at our ionosphere stations at various points of the USSR. The study of the absorption during the so-called "disturbed days" is very important. The question of the absorption of radio waves in the polar regions of the earth, which has been little investigated, is likewise of great theoretical and practical interest.

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